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Temporal humidity variations in the heritage climate of South East England

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Abstract

Humidity is an extremely important parameter in the protection of cultural heritage. Despite this its climatology has not been frequently studied. A range of instruments have been available for many years, but until recently accurate measurement has been problematic. Assessing average humidity has been difficult because of the wide diurnal and annual variation and the sensitivity of the water content of the air to temperature. Observations at Gatwick and Heathrow since the middle of the 20th century suggest a decrease in relative humidity, which may be as much as 10% in the summer months by the end of the 21st century. Estimates of salt damage and stress in wood, caused by day-to-day fluctuations in humidity for the rest of this century, are difficult to predict because increased dispersion in daily values. A careful analysis of the data structure suggests these pressures may be relative constant, such that salt weathering by halite is likely to be fairly constant through the coming century. However, the problems with the data structure indicated the danger in using sequential daily values from the UKCP09 projections. Indoors, taking the Cartoon Gallery at Knole near Sevenoaks as an example, suggests conditions will be reasonably constant over time. However, maintaining a lower indoor humidity close to 50% would likely involve the removal of much larger amounts of water during dehumidification in the future.

Keywords: Climate change, Dehumidification, Heritage climatology, Salt weathering, Wood deterioration

Introduction

Humidity is a critical threat to our material heritage. Its long term variation is thus of interest when considering damage in the past and that likely under a changed climate of the future. High humidity can promote metal corrosion and a wider range of effects by encouraging the deposition of pollutants and chemical reaction. It also allows the growth of fungi and bacteria on organic materials and the development of insect eggs and larvae. Low humidity can cause excessive drying and cracks in materials. Wide variations in relative humidity cause cycles of stress in materials such as wood.

The awareness of humidity as important element in the preventive conservation of indoor objects means it has been increasingly measured in indoor environments so as to meet standards for the heritage environment such as those laid out by Gary Thomson in his classic work *The Museum Environment* [1]. Standards continue to be updated e.g. the new British Standards Institution document and that of European Committee for Standardization [2]. The apparent ease of humidity measurement is illusory and there continue to be problems with accurate calibration and inter-comparison. Hygrometers have been available since the 17th century, with important work done by Horace Benedict de Saussure on the hair hygrometer. The approach to measuring humidity from the difference between the temperature of wet and dry bulbs of thermometers benefitted from studies by Richard Assmann in the 19th century. Although such measurements became part of regular meteorological monitoring, the data has never been as widely collected as temperature, rainfall and wind data. Hourly measurements depended on the development of modern electrical approaches to humidity determination. Problems of error in the measurements and the difficulties of making them regularly have meant that long time series have not been common. Despite this, longer term change in humidity from the perspective of heritage is important, especially so as

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this might shift with the climate predicted for the current century.

The long term variation of relative humidity for eastern England for the period 1920–95 has been studied for dendrochronological applications, using measurements from air force bases at Cranwell, Marham and Waddington [3]. Maps of monthly water vapour pressure are available from the UK Meteorological Office for the climate periods 1961–1990, 1971–2000, 1981–2010 (http://www.metoffice.gov.uk/public/weather/climate/maps). These summary data analyses, along with the projections for future climate, suggest increasingly dry conditions particularly in the summer which may have special relevance to salt damage for example [4].

This paper will examine the changes in humidity in south east England over a longer period (60 years) than the summary data analyses and also attempt to predict the likely changes through to the end of the 21st century. Additionally it will consider some potential threats to objects both outside and indoors. The current work was partly driven by the problems in establishing past values of humidity in research on the changes in insect populations in historic interiors [5]. This earlier study of Knole near Sevenoaks, revealed how few records of long term humidity were available and a particular lack of analysis for southern England, which has a fine collection of historic properties likely to be sensitive to a changing thermo-hygrometric climate.

Recent projects to examine the impact of long term climate change on cultural heritage, such as such as NOAH's ARK [6], have implied the need for a specialised climatology relevant to cultural heritage. The notion of climatology as a description of the generalised or average weather developed in the 19th century under Wladimir Peter Köppen, who was especially the interested in the relationship between plants and climate. Subsequently a range of more specific climatologies have developed; bioclimatology, ecological climatology, building climatology, material climatology etc. The heritage environment has most often been concerned with temperature and humidity thus describing a thermo-hygrometric climate. The Köppen classification of climate is essentially thermo-hyetal as it was constructed using seasonal temperature and precipitation and does not directly incorporate humidity. Beyond humidity, threats to cultural materials often include a range of additional factors, such as wind and pollution. These again are omitted in the classic Köppen description, hence the need for a heritage climatology [7]. This paper contributes to the understanding of these more specialised climates.

Method

Historical humidity records are much less common than those for temperature or rainfall. Camuffo et al. [8] have looked very carefully at the development of early hygrometric measurements from Northern Italy. These require very careful recalibration to bring them into line with modern methods. In the United Kingdom the wet and dry bulb thermometer or psychrometer has been available since the 19th century, especially after the work of Richard Assmann. Although the measurements made with this apparently simple equipment can be problematic, with considerable care being required in making the observations, This is especially a problem at lower temperatures where ice can form on the wet-bulb. There is also the potential for a systematic difference between the older wet-bulb/dry-bulb measurements and thin film capacitive sensor, but there no obvious disjunction over the length of the available records in the MIDAS data set used here.

Even when the instrumental errors are accounted for it is difficult to get a simple representation of the average daily humidity. In the case of temperature, the maximum-minimum thermometer invented by James Six in the 1780 s has allowed daily maximum and minimum temperatures to be averaged and to give a reasonable estimate of the daily average temperature. Daily average relative humidity can be a misleading concept due to its strong dependence on air temperature, so it will be necessary to be careful as to what it means. The lack of a simple equivalent to give the daily humidity has perhaps made long term records more difficult to assemble

Relative humidity is the most common descriptor of humidity, but it doesn't describe the amount of water in air; rather its relative saturation. Thus relative humidity represents the degree of saturation humidity, and is usually given as a percentage. The water content of the air can be presented in other ways that reflect the increasing in the capacity of air to hold water at higher temperature, e.g. absolute humidity (AH, grams of water in a cubic metre of air), or specific humidity which is based on the ratio of the mass of water and the mass of air. Other units, such as the mixing ratio (MR, grams of water in a kilogram of air) or the mole fraction are more fundamental, because they do not vary with temperature and pressure. However, in this paper absolute humidity will generally be used as the measure of the water content of air because it is volume based and we often need to consider the water content of rooms. These contain fixed volumes of air, but it is important to consider the problem when deriving the water content of indoor air using that outdoors. The interconversion between relative and absolute is complicated because of the non-linear relationship between water vapour pressure and temperature. Here the

Goff–Gratch relationship [9,10] has been used to formulate an expression:

$$AH = 0.478 \times 10^{6}\ RH \exp\left[\left(\theta\left(-7.859518 + 1.84408260\theta^{0.5}\right) + \theta^{3}\left(-11.78665 + 22.680740\theta^{0.5}\right) - 15.9618720\theta^{4} + 1.80122500\theta^{7.5}\right)647/T_a\right]/T_a$$

where $\theta = 1 - T_a/647$, T_a, absolute temperature K and AH and RH are the absolute and relative humidity. Because the calculations are so cumbersome, there are many on-line calculators (e.g. http://www.cactus2000.de/uk/unit/masshum.shtml).

Data sources and sites

There are a reasonable number of meteorological stations in the south of England. The data is held on-line at the British Atmospheric Data Centre (BADC) within the MIDAS dataset, which includes land and marine surface observations from 1853. It contains a wide range of parameters at daily and hourly frequency including temperature, rainfall, sunshine duration, radiation humidity among many others. Registered non-commercial users have ready access to this, although the size of the dataset requires that it is queried for specific parameters. The CEDA Web Processing Service (WPS), accessible from the BADC site, provides a web-based front-end for running user processes [11].

In gathering data to assemble a record for south east England the problem is more difficult than it might seem. The longest running site with wet and dry bulb temperatures at a non-coastal site is at the Royal Horticultural Society's garden at Wisley, a small village in Surrey, England (see the map in Figure 1). This location has seen notably high summer temperatures in the early 21st century. The record of relative humidity here begins in 1931, but as is so often the case with these records, measurements are typically available only for 0900 hrs each day because of the laborious nature of these observations. There is a long break in the Wisley record from 1958 until 1972. The most comprehensive hourly record is for Heathrow Airport. It begins with hourly readings in 1949. A further set is found at Gatwick Airport beginning in 1958 with eight humidity readings a day and continuous hourly readings from 1971.

Projections of future climate were taken from the UK climate projections (UKCP09) [12], which use Hadley model HadCM3 output [13]. Here only the A1F1 scenario was used as it gives the large changes in future climate, so can be thought to represent a type of worst-case. Maximum and minimum temperatures (averaged to give

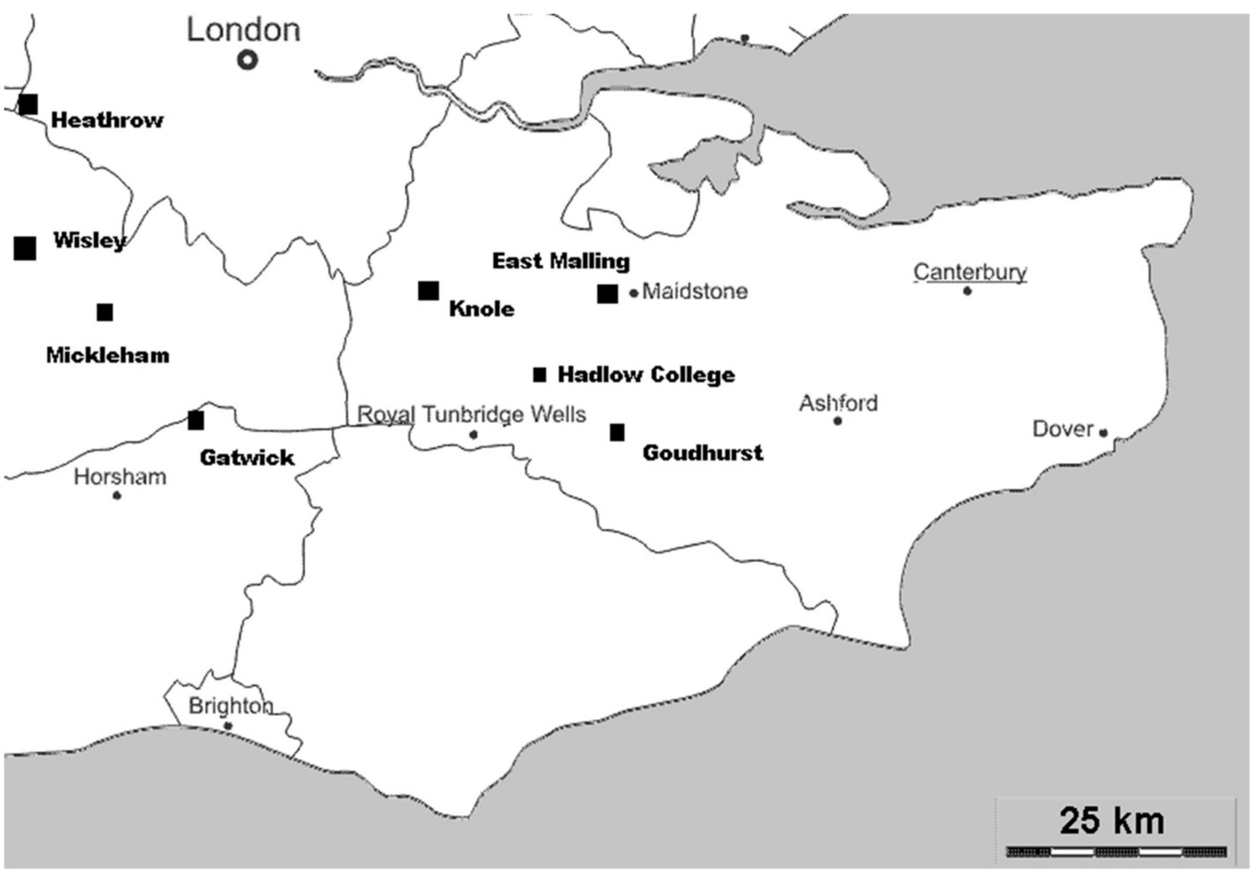

Figure 1 Map showing monitoring stations, key towns and cities and historic properties relevant to the text.

the daily mean) and relative humidity are available on a daily basis for thirty year periods from UKCP09 and can readily be re-evaluated a hundred times, essentially providing 3000 estimates of the daily weather conditions in each period. This gives an idea of the uncertainty to predictions. This output is available periods that centre on 2025, 2035, 2045, 2055, 2065, 2075 and 2085 in addition to a thirty-year baseline period at 1975. The UKCP09 weather generator allowed downscaling to an area 5 × 5 km, tuned to a specific site, in this instance Heathrow or Gatwick and produces plausible daily time series.

Southern England has a wide range of historic buildings, with many significant ones on display. As mentioned previously, some earlier research has focused on Knole near Sevenoaks. This important property is some 25 km to the north east of Gatwick airport. Lankester and Brimblecombe [14] developed transfer functions to determine the relation between outdoor climate and that within the Cartoon Gallery, which houses early copies of Raphael Cartoons dating from 1624. There are a number of other significant properties close to Heathrow, which include Ham House and Osterley Park and House. Some other meteorological sites in south east England that make relative humidity measurements are marked on the map in Figure 1, with details of their record listed in Table 1, but as noted many provide only a single measurement at 0900 hrs each day. This work has chosen inland sites representative of historic properties that are away from the coast where humidity is typically elevated by the proximity of the sea.

Data analysis and statistical methods

Much of the effort here will examine the behaviour in the long record of humidity at Heathrow, but Gatwick is examined as it is useful to consider in relation to climate within the Cartoon Gallery at Knole [5,14]. Even the simplest tasks when considering relative humidity can raise difficulties. Although average relative humidity is often reported, it is not necessarily clear that this is the appropriate measure of central tendency, particularly as relative humidity can take only values between the bounds at 0% and 100%,. Figure 2a shows the statistical distribution of the hourly measurements made at Heathrow 1951–1980. The distribution is not only skewed towards the lower values, but it is a bimodal distribution, with a large frequency at 100%. This is hardly surprising as it this represents saturated air. The mean of this data are 79.5% while the median is larger at 83.2%, which is to be expected with data that is negatively skewed.

Table 1 Weather stations with records of relative humidity available from the Meteorological Office MIDAS stations held at the British Atmospheric Data Centre (UKMO, 2012)

Station	Record	Frequency
Wisley	1931-[a]	Daily 0900
Heathrow	1949	Hourly
Gatwick	1958-	Hourly[b]
Goudhurst	1972-	Daily 0900
Hadlow Colg.	1972-93	Daily 0900
Mickleham	1972-	Daily 0900
Merrist Wood	1973-94	Daily 0900
East Malling	1994-	Daily 0900

[a] Mostly daily at 0900 hrs. A break occurs from 1958 until 1972. From 1931–32 0900, 1500 and 2100 readings and hourly in 21st century. [b] The early years of the record present data for every three hours, but it is hourly from 1971.

A further problem arises in defining the dispersion of the data. We usually describe this in terms of a standard deviation, but this assumes that the data follows a Gaussian or normal distribution. The data displayed in Figure 2a has a standard deviation of 15.2%. The average and dispersion of the measurements could thus be expressed as 79.5 ± 15.2%, but this also has a problem it would suggest a finite number of readings (9% of the data) would have a relative humidity greater than 100%. A standard deviation implies that 15.6% of the data lie more one standard deviation above or below the mean. The dispersion suggested by taking median and the percentage the data that lie around that median value would indicate 83.2 (+10.5 -20.7). The positive dispersion is much smaller than the negative dispersion, which is very much a characteristic of the distribution shown in Figure 2a. The central limit theorem would suggest that although the hourly values of *RH* fail to show a normal distribution, the daily averages should be better approximated by a normal distribution. In line with this, the distribution appears closer to a Gaussian curve, although a slight skew remains in the data plotted in Figure 2a as open squares.

At constant relative humidity the water content of the air increases with temperature and this can be expressed in a number of units, but here both absolute humidity as grams of water per cubic metre of air and the mixing ratio as grams of water per cubic metre of dry air are displayed in Figure 2b. It shows that these measures, absolute humidity and mixing ratio, reveal a dispersion that is close to a normal distribution. A particular problem with average relative humidity relates to the meaning of the average daily relative humidity when obtained from hourly values. Is this best represented as (i) the average of the hourly relative humidity values ($\sum RH_i$/24) or should it be determined from (ii) the daily average water content of the air (absolute humidity) and the daily average temperature. As shown in Figure 2c there is a reasonable agreement between these two methods of determination, so the former and simpler of these two methods is adopted here.

The UKCP09 projections are treated similarly in Figure 2d, where the probability distribution for daily

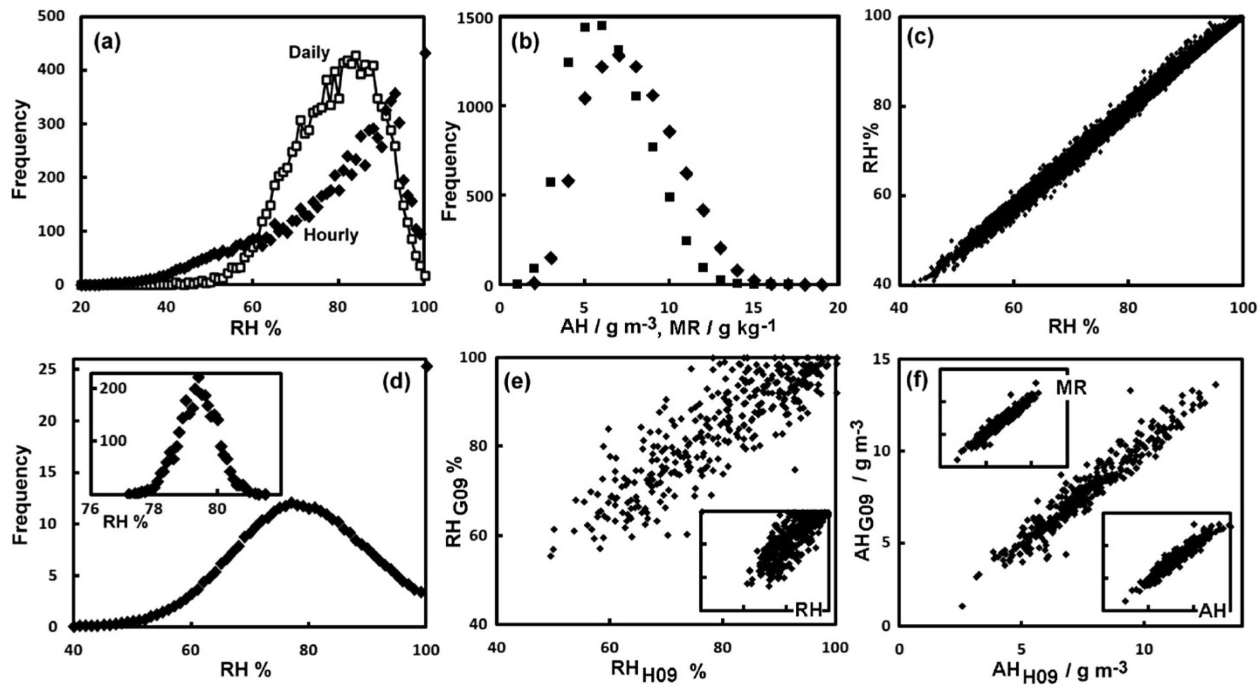

Figure 2 Statistical properties and of the Heathrow data and modeled output. (**a**) The probability distribution for Heathrow hourly and daily relative humidity 1961–1990. The hourly data is plotted as the number of occurrences each year at integer RH values, while the daily data is as the number of occurrences each year across the thirty year period. (**b**) The probability distribution for Heathrow hourly absolute humidity (diamonds) and mixing ratio (squares) 1961–1990 plotted as the number of occurrences each year at integer values. (**c**) Daily relative humidity calculated on the basis of summing hourly absolute humidity (RH') as a function of daily average relative humidity for the period 1949–2010. (**d**) The probability distribution for Heathrow daily relative humidity from the UKCP09 output for the 30 years centered at 1975 as the number of occurrences each year at integer RH values. Inset: the annual average RH for 3000 predictions as the number each year at integer RH values (**e**) The relative humidity at 0900 hrs for Gatwick RH_G as a function of that at Heathrow RH_H for 1972. Inset RH: RH_G measured at 0900 hrs the daily average RH for Gatwick 1972 - the tick marks have the same values as the larger figure. (**f**) The absolute humidity for 0900 hrs at Gatwick AH_G as a function of that at the same time at Heathrow AH_H for 1972. Inset AH: AH_G determined at 0900 hrs plotted against the daily average AH for Gatwick 1972 - the tick marks have the same values as the larger figure. Inset MR: The mixing ratio for Gatwick at 0900 hrs plotted against the mixing ratio at Heathrow for the same time in 1972 - the tick marks have the same values as the larger figure except that the units are g kg^{-1}.

and annual (see inset) relative humidity are shown. Note again the especially the very high value frequency of daily values for 100% relative humidity. Although this is large it is a not too different to the expectation that arises were we to assume that the values had a normal distribution and extend beyond relative humidity values greater than 100%. The annual average relative humidity values show an almost normal distribution as expected from the central limit theorem. The inset to Figure 2d and shows a near symmetrical distribution for the hundred runs from UKCP09 for a thirty-year period centred on 1975 (i.e. 3000 years of data).

The last two panes of Figure 2 compare Gatwick with Heathrow for data collected at 0900 hrs in 1972. These show that the correlation is much better for absolute humidity (Figure 2f) than relative humidity (Figure 2e): i.e. only 0.746 (RH) as compared with 0.929 (AH), so it may well be of advantage to attempting to compare stations, using absolute humidity. Note in particular how Gatwick has many more relative humidity values close to a hundred than Heathrow, as Heathrow tends to be a little warmer (an average of 9.6 compared to 10.5°C for the years 1961–1990). The insets in the lower right of both of these panes show the relationship between both relative and absolute humidity measured at 0900 hrs and the daily averages for 1972 data from Gatwick. Here the correlation coefficient, r^2 is 0.620 for relative humidity and 0.932 for absolute humidity, so once again, provided temperature data is available it may well be best to use absolute humidity in attempts to transform values at 0900 hrs to daily average humidity. The inset in the upper left of Figure 2f shows the average mixing ratio at 0900 hrs (units, g kg^{-1}) for Gatwick plotted against the mixing ratio at 0900 hrs for Heathrow in 1972. Again we see this measure of humidity, as with the absolute humidity, gives a better correlation (0.934) than relative humidity. These considerations mean that when comparing sites or when trying to estimate daily values from measurements available at only one time the transformation needs to be explored in terms of appropriate units.

However, this was not done in the current work as data analysis has been restricted to the two sites (Gatwick and Heathrow) that have sufficient hourly measurements to obtain average daily values.

In the following sections values from the MIDAS and UKCP09 databases is often presented as long-term trends or annual and diurnal cycles. These are typically plotted as medians and the dispersion is marked by the bars that show upper and lower percentiles that approximate a standard deviation. In the case of trends in the UKCP09 output this is as medians marked at the centre point of thirty-year periods (each one with a hundred sets of output) and here the dispersion is the 15.6 and 84.4-percentile, approximating the standard deviation. The MIDAS data is usually as medians of the slightly overlapping 11-year periods that embrace the decades, with dispersion marked by the 20 and 80-percentiles again to approximate the standard deviation, for the much smaller amount of data available as observations.

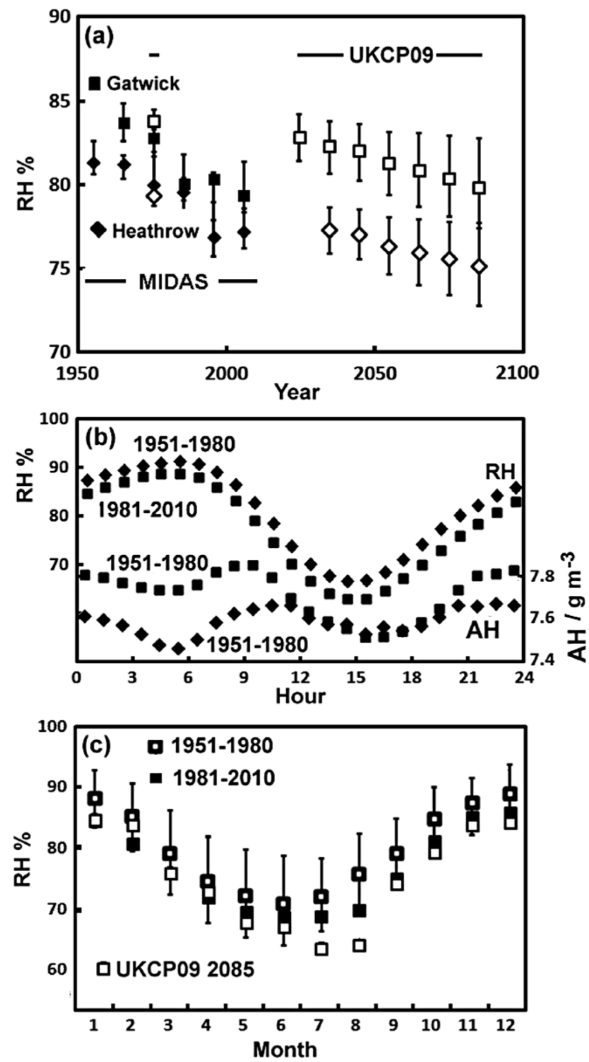

Figure 3 Relative humidity at Heathrow (diamonds) and Gatwick (squares). (**a**) The median of the annual averages for both the observed record, MIDAS – closed symbols and the projected values from UKCP09 - open symbols. Dispersion is marked by error bars approximating a standard deviation. (**b**) Daily cycle of observations for the thirty-year interval 1951–1980 to 1981–2010 for relative and absolute humidity in the MIDAS data for Heathrow and Gatwick (**c**).

Climatological results

The humidity climatology of south east England is illustrated in Figure 3. The long-term changes in relative humidity at both Heathrow and Gatwick are shown as median of the annual averages (Figure 3a) for both the observed record and the values from UKCP09. In the case of the observed values there are the medians of the slightly overlapping 11-year periods that embrace the decades. The dispersion is marked by the bars approximating one standard deviation. There is not a perfect overlap between the observations (closed symbols) and the UKCP09 predictions. The observations would suggest a more rapid decline in relative humidity, particularly at Gatwick, than would be predicted from the UKCP09 output.

This decline in relative humidity is in line with expectations from the analysis of the long record from Eastern England where there seems to be a decrease in relative humidity of more the one standard deviation across the period 1920–1995. The extensive analysis from gridded data in the UK [15] suggests that the vapour pressure over south East and central England increased by some 0.42 hPa 1961–2005. In terms of relative humidity if we take the annual mean temperature in south east England to have changed from 9.5 to 11.0°C over this period beginning with 10.2 hPa; it would imply a relative humidity change from 86% to 81%. Both these crude estimates indicate a drier air, which is expected as result of the warmer summers.

The diurnal cycle of relative and absolute humidity at Heathrow is shown in Figure 3b and shows that changes in the observations for the thirty-year interval 1951–1980 to 1981–2010. Absolute humidity is more evenly spread across the hours of the day, with averaged variation at just a few tenths of a gram of water in each cubic metre. The seasonal cycle (Figure 3c) naturally reflects the change between the damp of winter and the drier summer conditions. The dispersion around the median values are given, for clarity, only for the period 1951–1980, but these were similar for each of the other periods plotted. The UCKP09 baseline centred on thirty-year period in the future at 2085 has a similar form to the earlier periods of observations. As expected the relative humidity is lower in the later periods, with the most noticeable decrease in the UCKP09 predictions for the dry summer months of July and August at the end of the current century.

Damage

The protection of heritage considers a range to sources for damage, often thought of as the *nine agents of deterioration*: physical forces, theft and vandalism fire, water, pests, contaminants, light, incorrect temperature and incorrect relative humidity [16]. In spite being at the end of this list, humidity is often seem as a key driver for damage to indoor materials in contrast to outdoor damage, where it is water as a liquid is so important. However, humidity can be important even outdoors e.g. the damage to porous stone through salt damage. Salt weathering will be explored here as an example of outdoor damage.

Although heritage climatology has yet to be properly defined it would have to consider a wider range of meteorological parameters than the traditional Köppen climatology. Definitions need to draw upon bioclimatology and building and material climatology, but would characterise climate elements particularly relevant to heritage and recognise the importance of a number of critical meteorological parameters revelant to material heritage. These are not always the focus of traditional meteorological measurement. Additionally particular combinations of parameters could be damaging, such as rain followed by freezing conditions, which might cause severe frost damage to porous stone or high wind speeds and rain in terms driving rain, which forces water into porous building materials. It is also clear that some meteorological parameters accumulate, such that the number of degree days over given temperatures that promote insect growth [5] or high relative humidity causing mould growth or rusting. Subsequent sections will explore a few examples of using humidity data as an estimator for potential for damage to some cultural materials.

Outdoor salt damage

As salts crystallise within porous stonework pressure is exerted within the stone by the phase change. Repeated cycles of mechanical stress generated in this way lead to salt weathering. This process is especially damaging for hydrated salts which can exert much greater pressures within stone than unhydrated. However, even unhydrated can cause damage and disfigure stone facades [17]. The unhydrated salt, sodium chloride (halite), crystallises is close to 75.5%, a value which is not strongly dependent on temperature, so temperature could be neglected in the calculations of potential salt weathering. The number of crystallisation cycles can be estimated from counting the number of times relative humidity changes from above this critical humidity to a humidity below this value. It is difficult to assess how these humidity changes propagate into the pores of stone, but here the daily average is relative humidity adopted. This follows Grossi et al. [4] and uses of mean daily relative humidity on consecutive days and presumes that this 24-hour average takes some account of the buffering effect of the stone in the humidity transfer.

The estimated number of transitions for sodium chloride each year can be readily summed from the daily observations and also projected into the future using the output from UKCP09 (Figure 4a). The median number of salt transitions each year is displayed as closed and open diamonds for thirty year observational periods (i.e.1951-1980, 1961–1990, 1971–2000, 1981–2010) and the UKCP09 baseline period and the predictions of 30 years centred at 1975, 2035, 2045, 2055, 2065, 2075 and 2085, with dispersion as percentiles approximating a standard deviation. The estimated frequency of halite transitions from observations and predictions are not in agreement. Those from the UKCP09 output are significantly higher than those from the MIDAS data. This is true even for the 1975 baseline period where observations suggest some 44 transitions a year, compared to 67 for the predictions. Furthermore the MIDAS observations suggest an increase in salt transitions over time, while the UKCP09 output suggests a decline.

A closer analysis of the structure of day-to-day variation in the observed and UKCP09 output reveals a significant difference. The probability density functions of the relative humidity difference between subsequent days (RH_t - RH_{t-1}) for the two estimates of the frequency of transitions in the 1975 data shows that the UKCP09 output has much greater dispersion (Figure 4b). Clearly the greater the dispersion means that it is more likely that *RH* will be greater than 75.5% on the one day and less than 75.5% on the subsequent day. This seems to be the reason for the larger number of salt transitions estimated from the UKCP09 output.

Grossi et al. [4] observed that when the average relative humidity is close to the critical relative humidity for the salt transition there is likely to be a large the number of phase transitions. We can use this observation to speculate that the probability of a salt transition occurring is related to the tails of the probability density function on either side of the critical relative humidity (Figure 4c), such that the probability of a transition p_{TS} occurring from day t-1 to day t would be:

$$p_{TS} = 0.5\int_{RH=0}^{RH=\text{crit}} \varphi(RH)dRH \int_{RH=\text{crit}}^{RH=\infty} \varphi(RH)dRH = 0.5(p_0\ p_{-1})$$

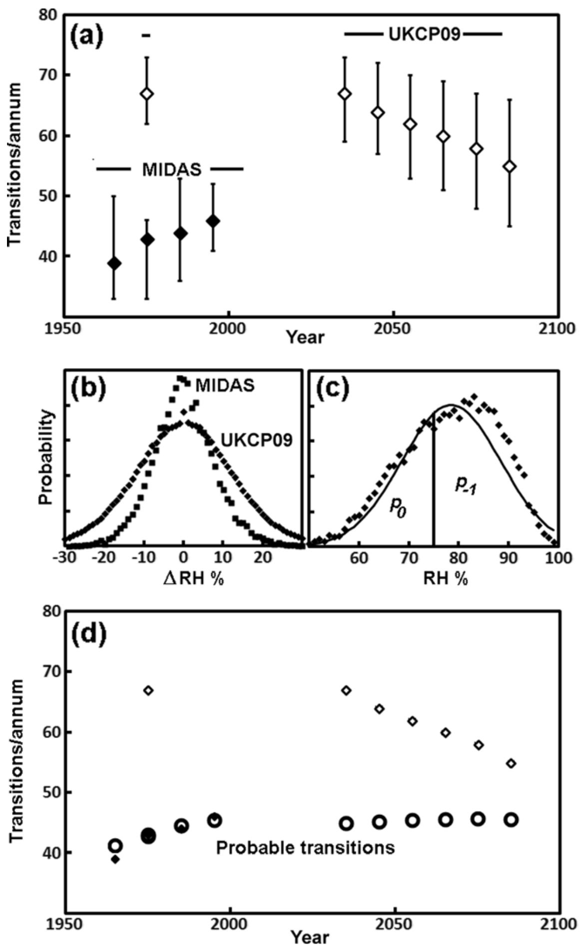

Figure 4 Potential for salt damage from sodium chloride crystallisation. (**a**) Median number of sodium chloride transitions per year are displayed as closed and open diamonds for thirty year observational periods from MIDAS observations those in the future using the output from UKCP09. (**b**) The probability density functions of the relative humidity difference between subsequent days (RH_t - RH_{t-1}) for the two estimates of the frequency of transitions in the 1975 data; arbitrary scale. (**c**) The probability distribution of relative humidity values from Heathrow 1949–2011; arbitrary scale. (**d**) Estimated median of sodium chloride transitions (open circles) per year estimated using the tails of the probability density function compared with the number of transitions counted in the UKCP09 output.

where $\phi(RH)$ is the value of the probability density function at a given RH value, p_{TS} the probability of a transition and crystallisation on subsequent days and p_0 p_{-1} are the integrals of the distribution where $RH <$ critical value and $RH >=$ critical value (75.5% for halite).

The expression has been halved because only half the transition will be from higher to lower values. It can be readily evaluated if we assume the distribution is normal such and have the annual mean of the daily relative humidity values and their standard deviation. The probable number of transitions calculated in this way are plotted as large circular symbols in Figure 4d. Those determined from UKCP09 projections agree well with the four observed medians for the thirty year periods 1951–1980, 1961–1990, 1971–2000 and 1981–2010. Those determined by simple counting of transitions appear as smaller symbols (the same values as those displayed in Figure 4a).

The predicted number of halite transitions increase through the late 20th century. The calculations suggest relatively little change in the future. This seems to meet our expectations as the annual average relative humidity will be close to the transition point of 75.5%; thus transitions are likely to be close to their maximum so were there further declines in relative humidity the number of transitions would eventually also show a decline. This calculation allows us to see why the two datasets failed to yield the same estimates for salt transitions and provides a more coherent view to the potential for salt weathering in the future. Nevertheless, it is hard to be certain that it gives an accurate picture, because of the different day-to-day variations embodied in the observed data and the UKCP09 output. It would be best to resolve this in terms of the underlying Hadley model rather than utilising the fix adopted here. Overall it serves as a warning about the care needed when demanding information at high time resolution (in this case day-to-day) from model projections of climate.

Outdoor wood damage

Variation in humidity can cause damage to organic materials such as wood. This has been of concern for considerable time as the warping and cracking of furniture and paintings has long been in evidence. A range of approaches to this have been used e.g. Lankester and Brimblecombe [14] used a table of potential damage suggested by Mecklenburg et al. [18] where particular variations in relative humidity were taken to cause permanent deformation. Such tabulations are not especially convenient for computation, so here the changes in daily relative humidity that induce stress in lime wood sufficient to lead to an irreversible response have been taken from Jakiela et al. [19]. Their work shows that relatively small changes at high humidity lead to irreversible deformation; at 100% it is around 8%, while in the mid-range around 50%, an almost 20% decrease in relative humidity can occur in a day without causing permanent damage. This highlights the wisdom of storing wooden objects at about 50% as here such daily changes seem likely to impose the smallest risks of irreversible dimensional stresses.

Over the period from 1949–2010 there were some 1500 events with the potential to cause irreversible

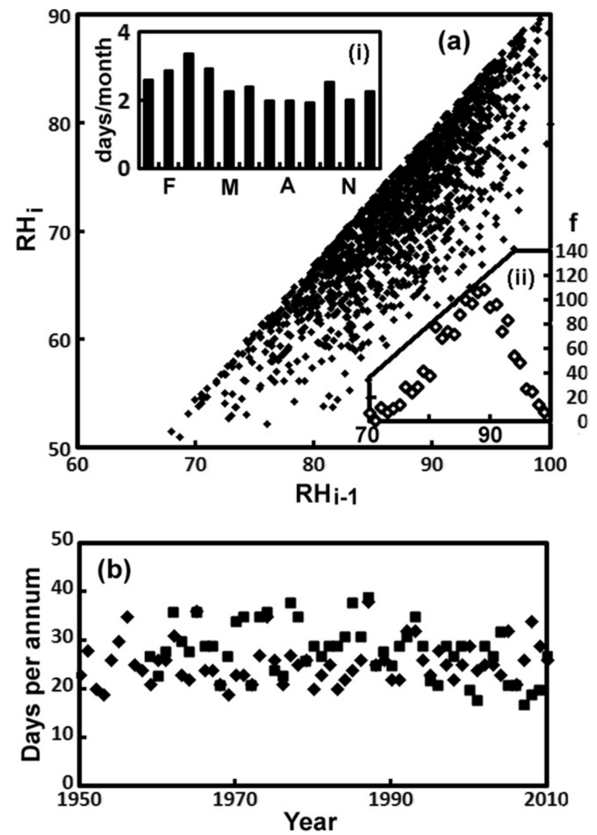

Figure 5 Potential damage to outdoor wood. (**a**) Initial and final relative humidity at Heathrow 1949–2011 for changes likely to cause irreversible deformation in lime wood. Inset (i): seasonal distribution as the number of days with irreversible deformation each month. Inset (ii) The initial daily relative humidity for events which cause irreversible deformation in lime wood. (**b**) The annual estimates of days likely to cause irreversible deformation to lime wood at Gatwick (diamonds) and Heathrow (squares).

damage in the climate record from Heathrow. Each of these plotted in Figure 5a which shows the initial and final relative humidity for these critical events. The threat to lime wood was determined using a simple program that counted days when the decrease in humidity on the subsequent day was large enough to lead irreversible deformation. Inset (i) to Figure 5a shows the seasonal distribution as the number of days each month likely to experience these damaging events while inset (ii) suggests that they are most frequent at relative humidity values around 90%. Thus it is days with these rare, but very high humidity values that are likely to impose the most critical stress on wood. The annual estimates of potential damage to outdoor wood, over the last 50–60 years for both Gatwick and Heathrow years show no clear trends (Figure 5b).

Indoor climate

The outdoor values of relative humidity can be used to estimate the indoor humidity using transfer functions. Lankester and Brimblecombe [14] developed some transfer functions for the Cartoon Gallery of Knole near Sevenoaks in Kent. These were developed as simplified methods of predicting indoor conditions from those outdoors. The approach was to correlate existing exterior thermohygrometric data with that of the interior using a simple linear function of the form: $y = ax + b$, where x is the daily outdoor temperature or specific/absolute humidity and y is daily indoor temperature or humidity. Different coefficients were determined for each month, to allow for seasonal variation in building ventilation. Temperature is very reliably predicted, but relative humidity much less so as occasionally the range of error is as high as 20%, but is generally much better than this as seen in the earlier work [14]. The method demands that the building will continuing to be used in the same manner, without structural changes or shifts in usage patterns.

The transfer function was been used here to estimate the past indoor humidity in the Cartoon Gallery from the Gatwick MIDAS data and the UKCP09 projections as shown in Figure 6a, which displays both the outdoor values (filled and open squares for MIDAS and UKCP09) and circles for the estimates of indoor conditions. Where existing indoor observations of humidity are available they agree reasonably well with the model estimates using the transfer function [14]. Indoor conditions are slightly drier than outdoors (Figure 6a) because of slightly warmer indoor temperatures, probably a result of solar gain. The figure also suggests that while the median relative humidity outside decreases, indoors it is rather stable. This arises because the predicted increases of temperature indoors are smaller than that outdoors [14].

The adaptation of Jakiela et al's approach [19] to predicting reversible damage to lime wood (Figure 6b) was used with estimates of the indoor relative humidity in the cartoon gallery. The values made using the MIDAS data (closed symbols) for Gatwick are much lower than those calculated from the UKCP09 projections (open symbols). This arises because a broader distribution of humidity values and a propensity for more at high humidity (compare Figure 2a with Figure 2d). The same overestimate was apparent (Figure 6c) from an attempt to estimate the number of damp days, (i.e. those greater than 90%). These damp days would fungi and mould to be more likely to grow (e.g. humidity temperature data of Polizzi et al. [20]). Again the frequency is much higher in the UKCP09 projections than for the MIDAS observations at both Heathrow (diamonds) and Gatwick (squares).

Earlier work [14] and the estimates of damage within the Cartoon Gallery made here, suggest decreasing damage if the humidity from sequential days is used. The

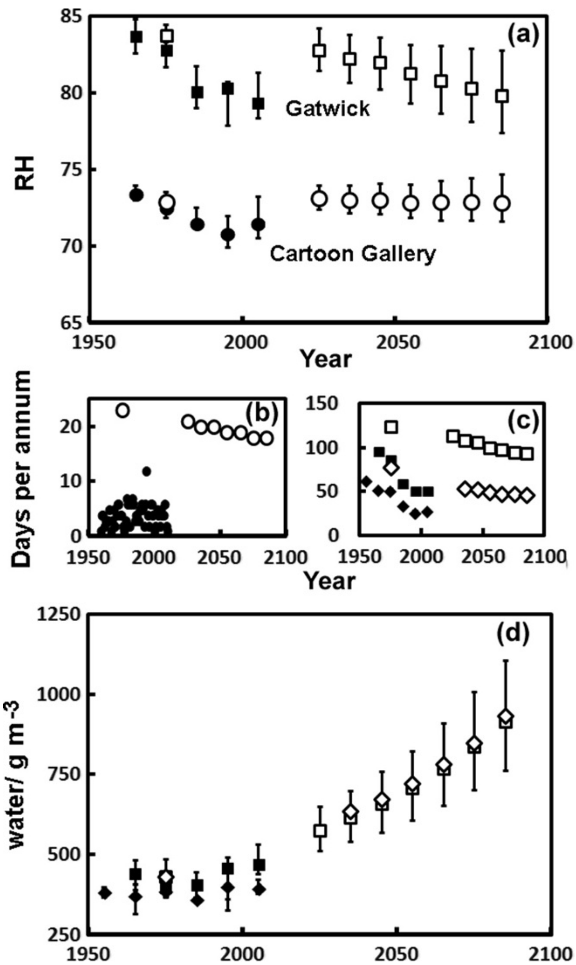

Figure 6 Indoor humidity estimates for the Cartoon Gallery at Knole. (**a**) Median of daily relative humidity for the Gatwick MIDAS data (filled symbols) and the UKCP09 projections (open symbols) and estimated indoor values for the Cartoon Gallery from MIDAS and UKCP09 humidity. (**b**) Days each year with the potential of irreversible damage to lime wood using the MIDAS data (closed symbols) and UKCP09 projections (open symbols) for Gatwick (**c**) Annual number of days from MIDAS (filled symbols) and UKCP09 (open symbols) with relative humidity greater than 90% Heathrow (diamonds) and Gatwick (squares). (**d**) Annual amount of water removal required over thirty year periods from the MIDAS and UKCP09 for Heathrow (diamonds) and Gatwick (squares) to maintain a relative humidity of 50%.

previous section hinted that projecting these results into the future is not easy because of the problem with the distributions of relative humidity as identified on subsequent days so should be avoided.

It is possible to undertake some calculations which avoid the use of sequential data. An example would be estimation of the amount water removal required each day for dehumidification. Janssen and Christensen [20] explored the optimisation of the thermo-hygrometric climate of museums and determined the large amount of water to be removed from the interior to maintain 50% relative humidity. This removal was typically required in summer where cooling imposed increases in humidity. Although summers in Europe of the future may well be slightly drier, the warm air would contain larger amounts of water vapour and if cooled would lead to high humidity, thus imposing the need for much water removal. The results in Figure 6d suggest increasing amounts of water would need to be removed by de-humidification in the future to maintain 50% relative humidity.

Conclusions

This work has shown that although there are few analyses of the long term humidity climate the data exists for a reasonable part of the century from a number of UK sites. However, at most sites this is restricted to measurements made at 0900 hrs and these might not be a good representation of daily values. The correlation of the humidity between sites some tens of kilometres apart in flat terrain is much better for absolute humidity or mixing ratio than for relative humidity. Attempts to fill in data at sites where there are only short records with that from adjacent sites might well start by examining correlation in terms of absolute humidity or mixing ratio, although optimum ways to do this would best be explored in future work.

There is of evidence of a reduction in relative humidity in south east England over the last half century and this is much in agreement with other analyses of observational data from England. Decreases are also predicted from the UKCP09 climate projections and seem to be particularly noticeable in July and August by the end of the 21st century. The decrease in median relative humidity over the last few decrease seems especially sharp and might be even greater that that apparent in the UKCP09 output. However, this difference would need to be explored further in future work.

Observational data would suggest an increase in the potential for salt damage over the last few decades, although it may have peaked now. Raw estimates of halite weathering from the UKCP09 output do not align with those from MIDAS as the underlying structure of the relative humidity projections, both in terms of their day-to-day variation and the frequency of high humidity (RH > 90%) are different. This also seems worthy of further investigation if we are to understand the potential for changes in salt damage, irreversible dimensional change in wood and fungal risk in risk through the coming century. However, observations over the last fifty years show no particular change in the day-to-day relative humidity that would increase the stresses in wood. The stress in wood is most likely to occur after very humid days (>90%) in south east England. The assembly of long term records of humidity, although not always a simple task, can give insight into the changing conditions and hint at the direction of change likely though the current century. They are an important part of understanding the response of cultural materials in past decades, but would also contribute to assessment of likely future change and thus aid heritage management.

Competing interests
The author declares that he has no competing interests.

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